

**BEHAVIOURAL BIOMETRICS BASED PERSONAL  
AUTHENTICATION: GAIT AND VOICE**

**M JEEVAN**



**DEPARTMENT OF ELECTRICAL ENGINEERING  
INDIAN INSTITUTE OF TECHNOLOGY DELHI  
SEPTEMBER 2017**

©Indian Institute of Technology Delhi (IITD), New Delhi, 2017

# **BEHAVIOURAL BIOMETRICS BASED PERSONAL AUTHENTICATION: GAIT AND VOICE**

by

**M JEEVAN**

Department of Electrical Engineering

Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy  
to the



**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**September 2017**

## **CERTIFICATE**

This is to certify that the thesis titled "**Behavioural Biometrics Based Personal Authentication: Gait And Voice** " being submitted by Mr. **M Jeevan** to the Department of Electrical Engineering, Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a record of bonafide research work carried out by him under our guidance and supervision. In our opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree.

The results contained in this thesis have not been submitted to any other university or institute for the award of any degree or diploma.

Date

New Delhi

**Dr. M. Hanmandlu**

Professor

Department of Electrical Engineering

Indian Institute of Technology Delhi

New Delhi-110016

**Dr. B.K.Panigrahi**

Professor

Department of Electrical Engineering

Indian Institute of Technology Delhi

New Delhi-110016

## **ACKNOWLEDGEMENTS**

Foremost, I pay my gratitude to my supervisors, Dr. M. Hanmandlu and Dr. B. K. Panigrahi for providing me the constant encouragement and guidance at every stage of my research. Without their strong support and spirited motivation I could not have achieved my research goals. I could not imagine having a better supervisors than them for my Ph.D. study. I extend my thanks to my SRC members, Prof. K. K. Biswas, Prof. S. D. Joshi, and Dr. Sumantra Dutta Roy for their fruitful suggestions and critical comments during my research presentation.

I am thankful to my lab mates Mamta, Neha, Sridevi and my seniors Amioy kumar, Jyotsana Grover and Venkat Chentala who supported me with valuable suggestions from their experiences that helped me to achieve my goals. Working with all of them has been a great pleasure and a lovable experience to me.

I am thankful to my friends Karthik, Army Venkat, Karan, Megha Shyam, Venkat Chental, Abhishek and Sucharitha who gave me a great moral support during my research.

I have no befitting words to express the love and affection of my mother Smt. Gangamani and my wife Mrs. Thota Anitha who are the pillars of my strength. Without their support and sacrifice I would not have reached this stage. A special thanks to my brother M Prem Kumar and my sister M Karuna for their support.

Finally, my greatest gratitude to the Almighty for his grace and mercy, and imparting me the passion and perseverance needed to complete the thesis successfully.

**M Jeevan**

## ABSTRACT

Biometrics is the measurement of information that emerges within or with the biological body such as face, iris, fingerprint, signature, voice, gait etc. A biometric system is essentially a pattern recognition system which makes a personal authentication by determining the specific physiological characteristics such as face, iris, ear, fingerprint, palm print, retina etc., or behavioural characteristics such as voice, gait, and gesture etc., possessed by the user. Behavioural biometrics is a form of biometric authentication that has shown promise to address the continuous frictionless authentication problem by allowing the device to identify the user without the user doing any explicit authentication actions while providing a strong form of authentication. Behavioural biometrics identifies users based upon their behaviour rather than upon fixed physical characteristic (such as a fingerprint). Behavioural biometrics learns patterns in user behaviour in order to build a user identification model and authenticates the user based on whether their behaviour conforms to the recorded model of the user behaviour.

In this thesis we have developed a multi-modal behavioural biometric based personal authentication system using Gait and Voice biometric traits, as they are challenging research areas in forensic, surveillance and personal authentication. We have formulated a Generalized New Entropy (GNE) function with free parameters as a generalization of the existing entropy functions to extract the gait entropy image. A variant of this entropy function called the dynamic entropy function is used in formulating the Dynamic Information Set based Particle swarm optimization (DISPSO) technique to learn the parameters. Two types of entropy features called GNE features and GNE based on Histogram of Oriented Gradients (GNE-HOG) features are formulated. The features are validated on three databases (CASIA, OUISIR Treadmill and SOTON small database) using Support Vector Machine (SVM),

Euclidean Classifier (EC) and Improved Hanman Classifier (IHC) which is an enhanced version of Hanman Classifier in the literature.

Next we have proposed Two-Fold Information Set (TFIS) features using Generalized New Entropy function and Information Set theory concepts. The TFIS gait features are extracted from Histogram of Oriented Gradients (HOG) descriptors for Gait recognition under speed variation. The proposed TFIS gait features are validated on three available databases: CASIA-C, OU-ISIR Treadmill-A and OU-ISIR Treadmill-D using Procrustes distance based classifier.

The TFIS voice features are proposed using Generalized New Entropy function and Information Set theory concepts for the text-independent speaker recognition. The extracted Mel Frequency Cepstral Coefficients (MFCC) from the speech signals of different speakers are converted into TFIS features that are classified by Improved Hanman Classifier (IHC), Support Vector Machine (SVM) and k-Nearest Neighbours (kNN). The proposed behavioural authentication system is tested on three datasets namely NIST-2003, VoxForge 2014 speech corpus and VCTK speech corpus and is found to reduce the feature size, computational time, and complexity and also improves the performance under the noisy environment.

The TFIS features that use type-1 membership functions discussed above are modified using type-2 membership functions leading to T2IS features. These features are the result of representing higher order uncertainty in the MFCC. We have also made use of Hanman transform which is another representation of higher order uncertainty. Unlike T2IS features, the Hanman transform features modify the MFCC features with a gain function which a function of the information values. Both these representations being higher order improve the performance of the voice based authentication system. This approach is not implemented on the gait based authentic system as the variations in shape and speed are adequately

represented by TFIS features and there is no substantial improvement in performance with higher order uncertainty representation.

We have modified the above multi-modal behavioural biometric authentication system based on refined scores used for the fusion of Gait and Voice modalities at the score level under the unconstrained conditions such as shape and speed variations in Gait and corrupted noisy speech signals in Voice.

## सार

बायोमेट्रिक्स जानकारी का माप है जो जैविक शरीर के भीतर या चेहरे, आईरिस, फिंगरप्रिंट, हस्ताक्षर, आवाज, चाल आदि जैसी उभरती है। एक बायोमेट्रिक प्रणाली अनिवार्य रूप से एक पैटर्न मान्यता प्रणाली है जो विशिष्ट शारीरिक विशेषताओं का निर्धारण करके व्यक्तिगत प्रमाणीकरण बनाती है। चेहरे, आईरिस, कान, फिंगरप्रिंट, हथेली प्रिंट, रेटिना इत्यादि, या उपयोगकर्ता द्वारा पास आवाज, चाल, और इशारा इत्यादि जैसे व्यवहार संबंधी विशेषताएं। व्यवहारिक बायोमेट्रिक्स बायोमेट्रिक प्रमाणीकरण का एक रूप है जिसने उपयोगकर्ता को पहचानने की अनुमति देकर निरंतर कठोर प्रमाणीकरण समस्या को संबोधित करने का वादा दिखाया है। व्यावहारिक बायोमेट्रिक्स उपयोगकर्ताओं को उनके व्यवहार के आधार पर निर्धारित भौतिक विशेषताओं (जैसे कि फिंगरप्रिंट) के बजाय पहचानते हैं। व्यवहारत्मक बायोमेट्रिक्स उपयोगकर्ता आइडेंटिफिकेशन मॉडल बनाने के लिए उपयोगकर्ता व्यवहार में पैटर्न सीखता है और इस पर आधारित उपयोगकर्ता को प्रमाणित करता है कि उनका व्यवहार उपयोगकर्ता व्यवहार के रिकॉर्ड किए गए मॉडल के अनुरूप है या नहीं।

इस थीसिस में हमने एक मल्टी-मोडल व्यवहार बायोमेट्रिक आधारित निजी प्रमाणीकरण प्रणाली विकसित की है, जो कि गेट और वायस बायोमेट्रिक लक्षणों का उपयोग करते हैं, क्योंकि वे फोरेंसिक, निगरानी और व्यक्तिगत प्रमाणीकरण में अनुसंधान के क्षेत्र चुनौतीपूर्ण हैं। हमने एक सामान्यीकृत नई एन्ट्रॉपी (जीएनई) फ़ंक्शन को मुक्त पैरामीटर के साथ तैयार किया है, क्योंकि मौजूदा एंट्रॉपी फ़ंक्शंस के सामान्यीकरण के रूप में गेट एंट्रॉपी छवि को निकालने के लिए। पैरामीटरों को जानने के लिए गतिशील सूचना सेट आधारित कण झुंड ऑप्टिमाइजेशन (डीआईएसपीएसओ) तकनीक को तैयार करने में गतिशील एन्ट्रॉपी फ़ंक्शन नामक इस एन्ट्रॉपी फ़ंक्शन के एक संस्करण का उपयोग किया जाता है दो प्रकार की एन्ट्रॉपी फीचर्स जीएनई फीचर्स और जीएनई, जिसे हिस्टोग्राम ऑफ ओरिएंटेड ग्रेडियंट्स (जीएनई-होग) की सुविधा के आधार पर तैयार किया गया है। इन सुविधाओं को सपोर्ट वेक्टर मशीन (एसवीएम), यूक्लिडियन क्लासिफायरियर (ईसी) और इम्प्रूव्ड हनमान क्लासिफायरफ़ायर (आईएचसी) का उपयोग करते हुए तीन डाटाबेस (कैसा, ओयूआईएसआईआर ट्रेडमिल और सॉटन छोटे डाटाबेस) पर मान्य किया गया है जो साहित्य में हनमान क्लासिफायरियर का एक उन्नत संस्करण है।

इसके बाद हमने सामान्यीकृत नई एंट्रॉपी फ़ंक्शन और सूचना सेट सिद्धांत अवधारणाओं का उपयोग करते हुए दो-गुना सूचना सेट (टीएफआईएस) का प्रस्ताव किया है। गति भिन्नता के तहत गेट मान्यता के लिए टीआईएफआईएस की चाल सुविधाओं को हिस्टोग्राम ऑफ ओरिएंटेड ग्रेडियंट्स (HOG) डिस्क्रिप्टर से निकाला जाता है प्रस्तावित टीएफआईएस की सुविधा तीन उपलब्ध डाटाबेसों पर मान्य है: कैसिया-सी, ओयू-

आईएसआईआर ट्रेडमिल-ए और ओयू-आईएसआईआर ट्रेडमिल-डी प्रोस्ट्रस्ट्स दूरी आधारित क्लासिफायरेटर का उपयोग कर।

पाठ-स्वतंत्र स्पीकर मान्यता के लिए सामान्यीकृत न्यू एन्ट्रॉपी फ़ंक्शन और सूचना सेट सिद्धांत अवधारणाओं का उपयोग करते हुए टीएफआईएस की आवाज़ें प्रस्तावित की जाती हैं। अलग-अलग वक्ताओं के भाषण संकेतों से निकाले गए मेल फ़्रिक्वेंसी सेप्ट्रॉल कोटेफिकेशंस (एमएफसीसी) को टीएफआईएस सुविधाओं में परिवर्तित किया गया है जिन्हें सुधारित हनमान क्लासिफायरियर (आईएचसी), सपोर्ट वेक्टर मशीन (एसवीएम) और कश्मीर के निकटतम नेबरर्स (केएनएन) द्वारा वर्गीकृत किया गया है। प्रस्तावित व्यवहार प्रमाणन प्रणाली एनआईटी - 2003, वॉक्सफॉर्ग 2014 वाक्चर कॉर्पस और वीसीटीके भाषण कॉर्पस जैसे तीन डेटासेट पर जांच की जाती है और यह फीचर आकार, कम्प्यूटेशनल समय और जटिलता को कम करने और शोर वातावरण के तहत प्रदर्शन में सुधार करने के लिए पाया जाता है।

हमने आवाज़ में आवाज़ और गति भिन्नता और ध्वनि में भ्रष्ट शोर भाषण संकेतों के रूप में अनियंत्रित शर्तों के तहत स्कोर स्तर पर चाल और ध्वनि रूपरेखा के संलयन के लिए इस्तेमाल परिष्कृत अंकों के आधार पर उपरोक्त बहु-मोडल व्यवहार बाँयोमीट्रिक प्रमाणीकरण प्रणाली को संशोधित किया है।

# TABLE OF CONTENTS

ACKNOWLEDGEMENTS .....	I
ABSTRACT.....	III
TABLE OF CONTENTS .....	VII
LIST OF FIGURES .....	XI
LIST OF TABLES .....	XIII
ABBREVIATION .....	XV
<b>CHAPTER 1. INTRODUCTION TO BIOMETRIC BASED AUTHENTICATION.....</b>	<b>1</b>
<b>1.1. A BRIEF REVIEW ON BIOMETRICS .....</b>	<b>1</b>
<b>1.2. BEHAVIOURAL BIOMETRICS .....</b>	<b>4</b>
<b>1.3. MOTIVATION.....</b>	<b>5</b>
1.3.1. <i>Gait recognition.....</i>	<i>5</i>
1.3.2. <i>Voice recognition.....</i>	<i>6</i>
<b>1.4. THE ISSUES ADDRESSED IN THIS THESIS .....</b>	<b>7</b>
<b>1.5. DIRECTIONS FOR ADDRESSING THE ABOVE ISSUES .....</b>	<b>8</b>
1.5.1. <i>Representation of Different Types of Uncertainty.....</i>	<i>8</i>
1.5.2. <i>Formulation of Information Sets.....</i>	<i>10</i>
1.5.3. <i>Formulation of Generalized New Entropy (GNE) function.....</i>	<i>10</i>
1.5.4. <i>Development of Information Set based features .....</i>	<i>10</i>
1.5.5. <i>Need for a Multimodal behavioural biometric system.....</i>	<i>11</i>
<b>1.6. THE ORGANIZATION OF THE THESIS .....</b>	<b>12</b>
<b>CHAPTER 2. GAIT RECOGNITION UNDER SHAPE VARIATIONS USING NEW ENTROPY BASED FEATURES .....</b>	<b>15</b>
<b>2.1. INTRODUCTION .....</b>	<b>15</b>
<b>2.2. LITERATURE SURVEY .....</b>	<b>17</b>
2.2.1. <i>Model based approaches .....</i>	<i>18</i>
2.2.2. <i>Appearance/Model free approaches .....</i>	<i>18</i>
2.2.3. <i>Motivation for the present work.....</i>	<i>20</i>
<b>2.3. RELATED TOPICS .....</b>	<b>20</b>
2.3.1. <i>Gait cycle extraction.....</i>	<i>20</i>

2.3.2.	<i>Histogram of Oriented Gradients (HOG)</i> .....	22
<b>2.4.</b>	<b>FRAME WORK FOR GAIT BASED AUTHENTICATION SYSTEM</b> .....	23
<b>2.5.</b>	<b>THE GENERALIZED NEW ENTROPY FUNCTION</b> .....	24
2.5.1.	<i>A brief review on the existing entropy functions</i> .....	24
2.5.2.	<i>The new entropy function</i> .....	25
<b>2.6.</b>	<b>ANALYZING ENTROPY FUNCTION WITH VARYING PARAMETERS</b> .....	29
2.6.1.	<i>Effect of varying parameter ‘<math>\alpha</math>’</i> .....	29
2.6.2.	<i>Effect of varying parameter ‘<math>\beta</math>’</i> .....	29
2.6.3.	<i>Effect of varying parameter ‘<math>a</math>’</i> .....	30
2.6.4.	<i>Effect of varying parameter ‘<math>b</math>’</i> .....	30
<b>2.7.</b>	<b>DYNAMIC INFORMATION SET BASED PARTICLE SWARM OPTIMIZATION (DISPSO)</b>	
	33	
2.7.1.	<i>Particle Swam Optimization (PSO)</i> .....	33
2.7.2.	<i>Dynamic Entropy Function</i> .....	35
2.7.3.	<i>Formulation of DISPSO</i> .....	37
2.7.4.	<i>A comparison of PSO and DISPSO</i> .....	43
<b>2.8.</b>	<b>FEATURE EXTRACTION</b> .....	44
<b>2.9.</b>	<b>HANMAN CLASSIFIER</b> .....	46
<b>2.10.</b>	<b>EXPERIMENTAL RESULTS</b> .....	48
2.10.1.	<i>Description of Databases</i> .....	48
2.10.2.	<i>Discussion of Results</i> .....	50
<b>2.11.</b>	<b>CONCLUSIONS</b> .....	55
 <b>CHAPTER 3. GAIT RECOGNITION UNDER SPEED VARIATIONS USING TFIS</b>		
<b>FEATURES</b>	.....	<b>57</b>
<b>3.1</b>	<b>INTRODUCTION</b> .....	57
<b>3.2</b>	<b>LITERATURE REVIEW</b> .....	57
3.2.1	<i>Model based approaches</i> .....	57
3.2.2	<i>Appearance-based approaches</i> .....	58
3.2.3	<i>Motivation</i> .....	60
<b>3.3</b>	<b>FRAMEWORK</b> .....	61
<b>3.4</b>	<b>THE PROPOSED METHODS</b> .....	62
3.4.1	<i>Information Set Theory</i> .....	62
3.4.2	<i>Proposed Two Fold Information Set (TFIS) feature</i> .....	65

3.4.3	<i>Proposed Procrustes distance based Classifier</i> .....	68
<b>3.5</b>	<b>EXPERIMENTAL RESULTS</b> .....	69
3.5.1	<i>Description of Databases:</i> .....	69
3.5.2	<i>Comparative analysis based on OU-ISIR-A dataset</i> .....	71
3.5.3	<i>Comparative analysis based on CASIA-C dataset</i> .....	75
3.5.4	<i>Comparative analysis based on OU-ISIR-D dataset</i> .....	77
<b>3.6</b>	<b>CONCLUSIONS</b> .....	78
<b>CHAPTER 4. TEXT-INDEPENDENT SPEAKER RECOGNITION USING TFIS</b>		
<b>FEATURES</b>	.....	<b>79</b>
<b>4.1</b>	<b>INTRODUCTION</b> .....	79
<b>4.2</b>	<b>LITERATURE REVIEW</b> .....	80
4.2.1	<i>Motivation</i> .....	83
<b>4.3</b>	<b>FEATURE EXTRACTION</b> .....	84
4.3.1	<i>Adapting Standard MFCCs to the proposed features</i> .....	84
4.3.2	<i>Extraction of TFIS features from speech samples</i> .....	85
<b>4.4</b>	<b>EXPERIMENTAL RESULTS</b> .....	86
4.4.1	<i>Description of Databases:</i> .....	86
4.4.2	<i>Discussion of Results:</i> .....	87
<b>4.5</b>	<b>CONCLUSIONS</b> .....	101
<b>CHAPTER 5. HIGHER ORDER INFORMATION SET BASED FEATURES FOR</b>		
<b>TEXT-INDEPENDENT SPEAKER RECOGNITION .....</b>		
<b>103</b>		
<b>5.1</b>	<b>INTRODUCTION</b> .....	103
5.1.1	<i>Motivation</i> .....	104
<b>5.2</b>	<b>HIGHER ORDER INFORMATION SET BASED FEATURES</b> .....	105
5.2.1	<i>Type-2 Information Sets based features</i> .....	105
5.2.2	<i>Hanman transform based features</i> .....	110
<b>5.3</b>	<b>EXPERIMENTAL RESULTS</b> .....	111
<b>5.4</b>	<b>CONCLUSIONS</b> .....	115
<b>CHAPTER 6. MULTIMODAL BEHAVIOURAL BIOMETRIC BASED</b>		
<b>AUTHENTICATION SYSTEM USING REFINED SCORES .....</b>		
<b>117</b>		
<b>6.1</b>	<b>INTRODUCTION</b> .....	117
<b>6.2</b>	<b>LITERATURE REVIEW</b> .....	118

6.2.1	<i>Fusion of Gait with other modalities</i> .....	119
6.2.2	<i>Fusion of Voice with other modalities</i> .....	120
6.2.3	<i>Motivation</i> .....	120
<b>6.3</b>	<b>THE PROPOSED MULTI-MODAL VERIFICATION SYSTEM</b> .....	121
<b>6.4</b>	<b>THE FUSION RULES</b> .....	122
6.4.1	<i>The Traditional fusion rules</i> .....	122
6.4.2	<i>The Proposed fusion rules</i> .....	123
<b>6.5</b>	<b>APPROACHES FOR AUTHENTICATION</b> .....	123
6.5.1	<i>Genuine and Imposter Scores</i> .....	123
6.5.2	<i>Conventional Score (CS) based verification</i> .....	124
6.5.3	<i>Refined score (RS) based verification</i> .....	124
<b>6.6</b>	<b>DATABASE USED</b> .....	126
6.6.1	<i>Gait database</i> .....	126
6.6.2	<i>Voice database</i> .....	127
<b>6.7</b>	<b>EXPERIMENTAL RESULTS</b> .....	129
6.7.1	<i>Results of Fusion</i> .....	131
<b>6.8</b>	<b>CONCLUSIONS</b> .....	141
<b>CHAPTER 7. CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK</b> .....		<b>143</b>
<b>7.1</b>	<b>CONCLUSIONS</b> .....	143
<b>7.2</b>	<b>CONTRIBUTIONS OF THE THESIS</b> .....	146
<b>7.3</b>	<b>LIMITATIONS OF THE THESIS</b> .....	147
<b>7.4</b>	<b>SUGGESTIONS FOR FUTURE WORK</b> .....	147
<b>REFERENCES</b> .....		<b>149</b>
<b>APPENDIX A</b> .....		<b>171</b>
<b>APPENDIX B</b> .....		<b>177</b>
<b>LIST OF PUBLICATIONS</b> .....		<b>185</b>
<b>BRIEF BIO-DATA OF AUTHOR</b> .....		<b>187</b>

## LIST OF FIGURES

<b>Fig. 1.1</b> Surveillance image that identifies subjects using their Gait.....	6
<b>Fig. 2.1</b> Schematic diagram of different phases in a gait cycle .....	21
<b>Fig. 2.2</b> Plot representation of gait cycles for a particular sequence of gait.....	21
<b>Fig. 2.3</b> HOG descriptors of individual silhouette.....	23
<b>Fig. 2.4</b> Proposed gait authentication system under shape variations .....	24
<b>Fig. 2.5</b> A plot of normalized Information gain.....	26
<b>Fig. 2.6</b> Entropy curves with varying parameter ' $\alpha$ ' .....	31
<b>Fig. 2.7</b> Entropy curves with varying parameter ' $\beta$ ' .....	32
<b>Fig. 2.8</b> Entropy curves with varying parameter ' $a$ ' .....	32
<b>Fig. 2.9</b> Entropy curves with varying parameter ' $b$ ' .....	33
<b>Fig. 2.10</b> Computation of the Entropy function value to be maximized during learning.....	41
<b>Fig. 2.11</b> Convergences of variables $x$ and $y$ for different numbers of particles ( $np$ ) and iterations ( $itr$ ) (a) $np=5$ , $itr=100$ , (b) $np=2$ , $itr=40$ and (c) $np=2$ , $itr=20$ .....	44
<b>Fig. 2.12</b> Entropy features extracted from a Gait cycle.....	45
<b>Fig. 2.13</b> ROC plots of (a) normal to bag (b) normal to cloth with EC.....	53
<b>Fig. 2.14</b> ROC plots of (a) normal to bag (b) normal to cloth with IHC.....	54
<b>Fig. 3.1</b> Proposed gait recognition system under speed variations.....	61
<b>Fig. 3.2</b> Proposed framework to extract TFIS features for gait recognition in under speed variations.....	65
<b>Fig. 3.3</b> A sample IR image from CASIA C database.....	70
<b>Fig. 3.4</b> Sample images of OU-ISIR-A from 2 km/h, 4 km/h and 7 km/h .....	71
<b>Fig. 4.1</b> Extraction of TFIS based Features for text independent speaker recognition .....	85
<b>Fig. 4.2</b> Text independent speaker recognition system.....	85
<b>Fig. 4.3</b> Clean speech TFIS feature vector representation of 3 users from top to bottom.....	88
<b>Fig. 4.4</b> Clean speech and noisy speech at 0dB, 10dB and 20dB TFIS data representation of a user.....	89
<b>Fig. 4.5</b> The first two elements of TFIS feature vector of 3 users.....	89
<b>Fig. 4.6</b> ROC of the average authentication of MFCC features using GMM-UBM on NIST-2003.....	96
<b>Fig. 4.7</b> ROC of the average authentication of MFCC features using GMM-UBM on VCTK .....	96

<b>Fig. 4.8</b> ROC of the average authentication of MFCC features using GMM-UBM on VoxForge .....	97
<b>Fig. 4.9</b> ROC of the average authentication of TFIS features using MHC on NIST-2003 .....	97
<b>Fig. 4.10</b> ROC of the average authentication of TFIS features using MHC on VCTK.....	98
<b>Fig. 4.11</b> ROC of the average authentication of TFIS features using MHC on VoxForge .....	98
<b>Fig. 5.1</b> Average recognition (%) in a noisy environment (white noise with SNR from 0dB to 30dB in steps of 5dB) of three databases with respect to scaling factor ( $\gamma$ ) .....	112
<b>Fig. 6.1</b> Multi-modal verification system .....	121
<b>Fig. 6.2</b> Block diagram showing Claimed sample, Query sample, Cohort samples, and their claimed score and cohort scores. ....	125
<b>Fig. 6.3</b> Flow chat for improved FRR and FAR based on Refined Scores.....	127
<b>Fig. 6.4</b> ROC plot comparing conventional and refined score based verification for (a) clean data and (b) constrained data .....	130
<b>Fig. 6.5</b> ROC of the average authentication using the CS based fusion on (a) BNN and SCC (b) BNN and SC0 (c) BNN and SC5 and RS based fusion on (d) BNN and SCC (e) BNN and SC0 (f) BNN and SC5 .....	133
<b>Fig. 6.6</b> ROC of the average authentication using the CS based fusion on (a) BNB and SCC (b) BNB and SC0 (c) BNB and SC5 and RS based fusion on (d) BNB and SCC (e) BNB and SC0 (f) BNB and SC5.....	135
<b>Fig. 6.7</b> ROC of the average authentication using the CS based fusion on (a) BNC and SCC (b) BNC and SC0 (c) BNC and SC5 and RS based fusion on (d) BNC and SCC (e) BNC and SC0 (f) BNC and SC5.....	136
<b>Fig. 6.8</b> ROC of the average authentication using the CS based fusion on (a) CNS and SCC (b) CNS and SC0 (c) CNS and SC5 and RS based fusion on (d) CNS and SCC (e) CNS and SC0 (f) CNS and SC5.....	137
<b>Fig. 6.9</b> ROC of the average authentication using the CS based fusion on (a) CNF and SCC (b) CNF and SC0 (c) CNF and SC5 and RS based fusion on (d) CNF and SCC (e) CNF and SC0 (f) CNF and SC5.....	138

## LIST OF TABLES

<b>Table 1.1</b> Different types of Biometrics with corresponding modalities .....	3
<b>Table 2.1</b> Recognition rates in % for different combinations of Database using SVM .....	51
<b>Table 2.2</b> Recognition rates in % for different combinations of Database using EC .....	51
<b>Table 2.3</b> Recognition rates in % for different combinations of Database using IHC .....	52
<b>Table 2.4</b> Comparison of GNE with IHC using the Standard PSO (SPSO) and DISPSO .....	52
<b>Table 2.5</b> Comparison with other Approaches .....	52
<b>Table 3.1</b> Recognition accuracy (%) across different walking speeds on OU-ISIR-A using TFIS features and Procrustes distance based Classifier (PC) .....	72
<b>Table 3.2</b> Comparison of average recognition accuracy (%) on each probe ranging from 2 km /h to 7 km/h and across the walking speeds of gallery from 2 km/h to 7 km/h using 1st, 2nd and TFIS features with Procrustes distance based classifiers (PC) on OU- ISIR-A .....	73
<b>Table 3.3</b> Average recognition accuracy (%) on each probe ranging from 2 km /h to 7 km/h and across the walking speeds of gallery from 2 km/h to 7 km/h using 2FInS features with different classifiers on OU-ISIR-A .....	73
<b>Table 3.4</b> Recognition accuracy (%) in different walking speeds with gallery speed of 5 km/h .....	74
<b>Table 3.5</b> Comparison of cross-speed gait recognition performance (%) with the proposed method .....	75
<b>Table 3.6</b> Comparison of recognition accuracy (%) with baseline methods on CASIA C dataset for gallery (fn) .....	76
<b>Table 3.7</b> Comparison of recognition accuracy (%) with state-of-the-art methods on CASIA C dataset .....	76
<b>Table 3.8</b> Comparison of recognition accuracy (%) with state-of-the-art methods on OU- ISIR-D database .....	77
<b>Table 4.1</b> Correlation coefficient matrix for 3 users .....	90
<b>Table 4.2</b> A comparison of Average k-fold identification accuracy (%) on NIST-2003 .....	92
<b>Table 4.3</b> A comparison of Average k-fold identification accuracy (%) on VoxForge .....	93
<b>Table 4.4</b> A comparison of Average k-fold identification accuracy (%) on VCTK .....	94
<b>Table 4.5</b> Average number of features per sample approximately .....	95

<b>Table 4.6</b> Performance evaluation of MFCC features using GAR and EER on 3 different databases .....	100
<b>Table 4.7</b> Performance evaluation of TFIS features using GAR and EER on 3 different databases .....	100
<b>Table 5.1</b> A comparison of Average k-fold identification accuracy (%) on NIST .....	112
<b>Table 5.2</b> A comparison of Average k-fold identification accuracy (%) on voxForge.....	113
<b>Table 5.3</b> A comparison of Average k-fold identification accuracy (%) on VCTK .....	113
<b>Table 5.4</b> Average k-fold identification accuracy (%) using Hanman transform features on three databases .....	114
<b>Table 5.5</b> Average number of features per sample approximately .....	114
<b>Table 5.6</b> Approximated average time (sec) taken to complete identification process of all users per sample as test, with white noise and at a snr. ....	114
<b>Table 6.1</b> Different databases based on training and testing.....	128
<b>Table 6.2</b> EER (%) of individual databases (clean and constrained) using CS and RS.....	130
<b>Table 6.3</b> GAR (%) of individual databases (clean and constrained) using CS and RS for FAR=0.01 and FAR=0.1 .....	131
<b>Table 6.4</b> EER (%) for fusion of databases using CS and RS.....	139
<b>Table 6.5</b> GAR (%) for fusion of databases using CS and RS.....	140

## ABBREVIATION

Full Name	Abbreviation	Symbol
Gain function		$G$
Membership function		$\mathcal{G}$
Information Set		$\mathcal{H}$
Effective Information		$H$
Gait score		$\mathcal{S}_{gait}$
Voice score		$\mathcal{S}_{voice}$
Score		$\mathcal{S}$
Genuine score		$\mathcal{GS}$
Imposter score		$\mathcal{IS}$
Histogram of Oriented Gradients	HOG	
Generalized New Entropy image	GNE	
Generalized New Entropy on Histogram of Oriented Gradient image	GNE-HOG	
Particle Swam Optimization	PSO	
Dynamic Information Set based Particle Swam Optimization	DISPSO	
Two-Fold Information Set features	TFIS	
Type-2 Information Set features	T2IS	
Hanman Transform features	HT	
Mel-Frequency Cepstral Coefficients	MFCC	
Euclidean Classifier	EC	
Support Vector Machine	SVM	
k Nearest Neighborhood	kNN	

Hanman Classifier	HC
Improved Hanman Classifier	IHC
Modified Hanman Classifier	MHC
Procrustes Classifier	PC
Receiver Operating Characteristic	ROC
False Acceptance rate	FAR
False Rejection rate	FRR
Genuine Acceptance rate	GAR
Conventional Score	CS
Refined score	RS
Gait Energy Image	GEI
Gait Entropy Image	GEnI
Gait Pal and Pal Entropy	GPPE
Gait Susan-Hanman Entropy	GSHE
Gait Information Image	GII
Procrustes Shape Analysis	PSA
Fourier Descriptor	FD
Motion Energy Image	MEI